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# Prioritizing Sustainable Development Criteria Affecting Open Pit Mine Design: A Mathematical Model

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**Abstract**

With growing awareness of sustainable development and worldwide interest in corporate sustainability, the mining industry is under increasing pressure to design and plan not only based on geological, economical and technical factors, but also in accordance with sustainable development principles. Sustainable mining covers environmental, economic and social aspects of operations. In order to internalize sustainability in the mine design process, this paper attempts to quantify sustainable development criteria. Initially, 77 indicators of sustainable development affecting the open pit mine design were identified. By means of a preference voting system (PVS), the weight of each criterion was calculated. To reach this purpose, 4 importance levels: {Really Important, Quite Important, Less Important, Not Important} have been defined, where these importance levels represent the importance from the most to the least. It is clear that the votes in the last importance level (i.e. Not Important) should not influence the total score of each criterion. So, the weight of this importance level was considered equal to zero and then applied to a data envelopment model (DEA) based on 3 importance levels as ranking places to calculate the weights. Then the score and normalized weight of each criterion was calculated. Thus, the compatibility of mine design and the sustainable development issue can be measured via the sum of satisfied criterion weights.

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*Keywords: Sustainable development; open pit mine design; preference voting system; data envelopment analysis.*

## 1. Introduction

The population growth in the world-increased demand for industrial product development and economic growth has caused increase in mining products and activities. In most countries, surface mining methods have the most

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important role in ore production, so that 97 percent of mines in Iran have been mined by surface mining methods. In recent years, the development of surface mining activities has adverse impacts on mined lands. The studies in Iran show that almost 393 million tons of metallic and non-metallic ore are mined by surface mining methods, more than 900 hectares are disturbed by mining activities as pit, waste dumps and tailing dams, the lack of attention to undesirable issues is in conflict to sustainable development criteria in open pit mining project. It is expected that within a period of 20 to 30 years the consumption of minerals will increase by a **factor of about 2**. This means lower grade ores are going to be exploited and, as a result, more waste and tailing are going to be generated in the stripping and processing stages, respectively. Therefore, in 20 to 30 years from now, the mining activities will have 4 main characteristics and they are (1) the ore grades are lower than present, (2) ore will be mined from deeper than now, (3) larger amount of waste must be removed in order to reach lower grade ores from depth, and (4) the scale of mines will change from large to Giant Mines which requires a production per day (ore and waste) increase to more than one million tons per day [1].

The concept of sustainable development gained international recognition at the United Nation's Earth Summit Conference in Rio de Janeiro, Brazil in 1992. Sustainable
development has been defined as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. The main concept of sustainable development in mining activities is the management of resources in such a way that they can be mined by future generations.

The mining industry has focused on improving its environmental and social performance to improve its characteristics toward the sustainable development issues to become more efficient and economical in its operations. Regarding the sustainability assessment of a mine, many assessments focus on environmental protection with little mention of social and economic issues [3].

Von Below (1993) by considering the impacts of depleting resources and environmental degradation caused by mining emphasized the importance of continued and on-going mineral exploration, technological innovation, and environmental rehabilitation [4]. Allan (1995) defined sustainable mining in the cases where the rate of mineral usage does not exceed the capacity to find new resources, acceptable substitutes or recycling [5]. On the other hand, sustainability includes an environmental component, and miners should take care of the mined lands. The conventional approach whereby miners can achieve sustainable development by embracing social, environment and economic concerns, was presented by James in 1999 [6]. Folchi (2003) developed a procedure to quantify the environmental impact of a mining operation in Sardinia [7]. Odell (2004) also emphasized not only the environmental impact but also the social and economic impacts of mining operations taking into consideration the principles of sustainability at the mine design stage [8]. Corder and colleagues (2010) attempted to develop a new method for internalizing the principles of sustainable development into the mine design and mineral processes [9]. The aspects and current state of mining activities was discussed by Randolph in 2011 [10]. Also Laurence (2011) reviewed the literature on sustainable development in the mining industry with the purpose of providing mine operators with guidance on improving the sustainability of their sites [11]. Others, such as Osanloo et al. (2008, 2011), investigated the environmental impact of mining in mine planning and cutoff grade determination [12,13]. Rahmanpour & Osanloo (2012) noted the significance of premature mine closure in modern mines planning [14]. A combination of green mining, giant-scale mining and lean mining with enormous amounts of waste removal was predicted by Rahmanpour & Osanloo in 2012 as the future of mining projects [15]. Rahmanpour & Osanloo (2013) proposed sustainable development and sustainable mining as the key factors of the future mine design and planning and determined the sustainable Sungun mine design by applying the Folchi method for assessing the sustainability of the mine design [16]. Phillips (2013) developed a mathematical model to determine the level of sustainable development in mining operations [17]. Due to the adverse impacts of mining on the environment, both during and past mining operations, Rahmanpour & Osanloo (2013) used a mathematical model based on the Environmental Impact Assessment (EIA) to evaluate the sustainability of the Sungun mine [1]. Narrei & Osanloo (2011, 2014) considered the revenues obtained through a reduction of the environmental impacts in her optimum cut off grades model [18, 19]. Recently, Xiao-chuan XU (2014) reported the impacts of the ecological costs associated with iron mines in China on the ultimate pit limit design was reducing the economic profitability of the final pit [20]. Studies show that in the future, mining activities must follow a practice of Green Mining as a prerequisite of sustainable mining [20]. The main objective for the optimization of mining operations is maximizing the net present value of the mining project, but this main is not actually considered an optimum design regardless of sustainable development aspects in the planning stage of the project.

The purpose of this study is to applying sustainability principles at the early stages in the ultimate pit limit design by prioritizing sustainable development criteria affecting open pit mine design and then the risks of project should be in an acceptable range to be assumed as a justified reason for investment.

Due to the significance of the ultimate pit limit design stage in modern open pit mining, the present study attempts to quantify sustainable development criteria affecting the open pit mine design. Initially, 77 criteria of sustainable development affecting the open pit mine design are identified and then a preference voting system (PVS) based on a model of data envelopment analysis (DEA) is applied to weight rather than the decision theory. The difference between this PVS with similar cases in the past researches is the process of calculating the weights of ranking places. This PVS has applied a model of data envelopment analysis (DEA) to calculate the weights. This DEA model is based on 3 importance levels as ranking places to calculate the weights. Thereupon the score and normalized weight of each criterion has been calculated.

## 2. Mine design incorporating sustainable development criteria

Sustainable mining is the other aspect of future mining activities; therefore, the environmental, economic, and social aspect of sustainable development should be considered in any mine design and planning. It is expected that future mining operations is going to produce more than one million tons of low grade ore. The reduction in cutoff grade by demand for mineral raw materials and technology progress in equipment capacity causes an increase of the stripping ratio and larger-scale mining [21].

Sustainable development in mining means investing in the projects that are economically profitable, technically suitable, environmentally responsible and socially accepted. Nowadays, the issue of sustainable development has changed the conventional definitions of mining and modern mining as a term has been proposed.

Sustainable mine design includes determining the ultimate pit limit and planning of optimum annual production with the aim of maximizing the net present value considering the sustainable development criteria. Open pit mine sustainable design is one of the most important issues which makes mining projects profitable in all three aspects: environmental, economic and social. Sustainability in mine design and planning is considered a cost-effective method to reduce the environmental, social and economic risks, which increases opportunities during the mining life cycle.

The world's population in 2010 was more than 7 billion and it is expected that the population will reach 8.3 billion based on a population growth rate of 2 %. On the other hand, the mineral consumption during the past 10 years has been increased with a rate of 1 to 3 %. If the per capita consumption of mineral in developed countries is assumed to be constant which equals to 1700 tons, thus during the next 20 years, 3600 billion tons of mineral must be produced. It is also expected approximately 56 billion tons of waste will be generated in 2030 [21].

The areas of lands affected by mining activity have been increased in larger mines challenging this industry in the context of sustainable development. The study of sustainable development includes in the scale of mines. In fact, this issue refers to the significance of scale of mine and its impact on reducing the mining costs. Due to the above cases, it can be concluded the small mines with low reserves and low production capacity have less adverse impacts on the aim of sustainable development.

## 3. A new approach prioritizing sustainable development criteria

According to the decision-making methods, a great deal of research is performed recently in order to solve problems using multi-criteria decision-making method. In the multi-criteria decision problems, each alternative is evaluated by several criteria and also prioritizing alternatives carry out through determining the importance levels of criteria or paired comparisons between alternatives and criteria. In these methods, qualitative criteria convert into quantitative ones which can be compared with each other and the importance levels and priority of each alternative is determined and finally the best one is selected. Generally, the preferable alternative selection process by decision-making methods can be divided into two steps:

Step One: Calculating the weights of the criteria

Step Two: Selecting the most appropriate alternative according to criteria

According to previous studies, there were two major problems in applying decision-making methods in selecting the most appropriate alternative:

A) Calculating the weight of each criterion in the first step

B) Ambiguity in the judgment of decision-makers in the first and second step

According to the first step, using the analytic hierarchy process (AHP) has been a common approach to calculate the weights of criteria in recent years. Since plenty of the quantitative and qualitative sustainable development criteria are involved with the mine design, it seems the paired comparisons of criteria in the AHP method on this issue is very exhausting. In addition, the problem-solving process will be very time consuming and may eventually leads to false results. This is possible due to incompatibilities and further surveys are needed. Some researchers have attempted to reduce the dimensions of the paired comparisons matrix, encountering this problem. In this regard, Zare Naghdei et al. [22] have selected the main criteria from among all criteria and their calculations are performed based on them in their study on the most appropriate mining method. It is obvious that some criteria involved in the problem have been removed by this approach. Also some other researchers such as Alpay et al. (2009) [23], Namin et al. (2009) [24], Mikaeil et al. (2009) [25] and Azadeh et al. (2010) [26] have classified the criteria into distinct groups to reduce the dimensions of the paired comparisons matrix that this approach has evidently prevented a comparison of the individual criteria in the different subgroups and sufficed to compare criteria in each subgroup and compare groups with each other. Furthermore, despite using this approach, the time consuming calculation has still remained a major problem. Aside from the AHP method, some researchers have applied preference voting system (PVS) to calculate the weights of criteria which reduced the computation greatly; however the weights of ranking places were defined in a manner quite subjective. The remaining approaches used linguistic expressions to calculate the weights, indicating that this approach also seems to be quite subjective. On the other hand the researchers have used a fuzzy approach in dealing with the second problem at this stage (ie, the ambiguity in the judgment) which adds to the volume of calculations.

According to the second step, several techniques such as AHP, TOPSIS and PROMETHEE, were used to solve the problem of ambiguity that the decision makers were faced with at this stage and a fuzzy approach was applied to deal with it again. This study is an attempt to overcome the above problems and achieve results that are more reliable. In this regard, a new approach has been proposed to calculate the weights of sustainable development criteria affecting the open pit mine design. The proposed approach has used a PVS. How to calculate the weights of ranking places is the difference between PVS and the similar cases in previous researches. The PVS used a model of Data Envelopment Analysis (DEA) to calculate the weights. By using this approach, applying subjective decisions about weights of ranking places has been reduced and the results will be more reliable.

On the other hand, in this approach, the decision makers set only the priorities (rather than the value of priority), ambiguity in the judgment will be also reduced in a simpler method of fuzzy approach. Furthermore, by reducing the computational effort, involving all criteria will be possible. Moreover, by this approach, benefiting from the advantages of group decision-making with a large number of decision makers will be easily accomplished.

### *3.1. Preference Voting System (Pvs)*

In these systems, each voter selects *m* candidates from among *n* candidates and arranges them from highest to lowest priority. Each candidate may obtain numbers of votes in each ranking place. The total score of each candidate is the sum of the weights of votes that each candidate has achieved in various ranking places [27], which is defined according to equation 1.

$$z_i = \sum_{j=1}^{m} v_{ij} w_j \qquad i = 1,\ldots,n. \tag{1}$$

$w_j$ is the importance or in other words the weight of *j*-th ranking place $(j = 1,\ldots,m)$ and $v_{ij}$ is the number of votes which *i*-th candidate in *j*-th ranking place has achieved. The structure of calculation in PVS has been shown in table 1.

In this structure, the winner will be the one, which has achieved the highest total score. So it is obvious that the key issue in the aggregation of votes in PVS, will be how to calculate the weights of the ranking places (ie, $w_j$). The Broda-Kendall method is a well-known method in calculating the weights. This method assigns the weights ( $m, m-1, m-2,\ldots,1$ ) to *m* ranking places from the most to the least importance respectively.

In this method, the weights are generated simply but the calculating process is quite subjective. Cook and Kress [28] have applied a data envelopment analysis (DEA) to generate weights for PVS in order to reduce applying the subjectivity in weighting process that in this approach the candidates were considered as Decision Making Units (DMUs). DEA method is based on a linear programming that Charnes and his colleagues presented it in 1978. This method is used for evaluating the relative efficiency of decision-making units, which are doing the same tasks.

Table1-The PVS Structure.

| Candidates | Ranking Places | | | | | Total Scores |
|---|---|---|---|---|---|---|
| | $p_1$ | $\cdots$ | $p_j$ | $\cdots$ | $p_m$ | |
| | Weights of ranking places | | | | | |
| | $w_1$ | $\cdots$ | $w_j$ | $\cdots$ | $w_m$ | |
| | Vote of each candidate in each ranking place | | | | | |
| $candidate_1$ | $v_{11}$ | $\cdots$ | $v_{1j}$ | $\cdots$ | $v_{1m}$ | $z_1 = \sum_{j=1}^{m} v_{1j} w_j$ |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $candidate_i$ | $v_{i1}$ | $\cdots$ | $v_{ij}$ | $\cdots$ | $v_{im}$ | $z_i = \sum_{j=1}^{m} v_{ij} w_j$ |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $candidate_n$ | $v_{n1}$ | $\cdots$ | $v_{nj}$ | $\cdots$ | $v_{nm}$ | $z_n = \sum_{j=1}^{m} v_{nj} w_j$ |

The model proposed by Cook and Kress [28] has calculated the weight of each candidate, which maximizes the total score of the candidate. Thus, the model is solved once for each candidate, its total score is calculated, and eventually the candidate with the highest score from number one, was reported as an effective option. The proposed model is shown in equation 2.

$$\text{Maximize } \; z_i = \sum_{j=1}^{m} v_{ij} w_j$$

$$\text{to } \; \sum_{j=1}^{m} v_{ij} w_j \le 1 \quad \text{Subject}\, i = 1,\ldots,n \tag{2}$$

$$w_j - w_{j+1} \ge d(j,\varepsilon) \quad j = 1,\ldots,m-1 \quad w_m \ge d(m,\varepsilon)$$

where: $d(\,.\,,\varepsilon)$ is Discrimination Intensity Function (DIF) in the model. It is obvious that the approach is based on the DEA mentioned above, does not require calculating the weights of ranking places subjectively and would be desirable.

### *3.2. Sustainable development criteria affecting the open pit mine design*

The most significant principle in obtaining sustainable development through the expansion of mining and mineral industries is the consideration of environmental, economic and social criteria simultaneously. The implementation of sustainable development criteria is particularly important in open pit mine design. For each of the main criteria, sub-criteria are also considered, because the lack of attention to these sub-criteria in open pit mine design causes unsustainability in mine planning.

### *3.3. The proposed hierarchy preference voting system (hpvs) approach*

In this approach, the calculating weights and prioritizing the sustainable development criteria affecting open pit mine design is illustrated in Fig. 1 as a hierarchical structure.

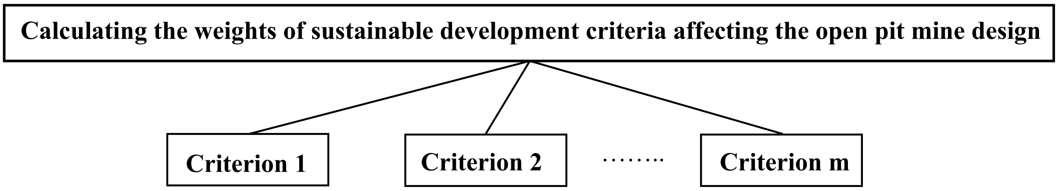


Fig. 1. The structure of hierarchy preference voting system (HPVS).

### *3.4. Prioritizing sub-criteria based on its importance on sustainable mine design*

A preference voting system (PVS) is used in this approach to calculate the weight of each criterion. It is worth noting that the group decision making in the methods mentioned, requires a lot of computational effort while it is simply accomplished by PVS. The PVS structure associated with criteria is indicated in Table 2.

Table 2. The PVS structure associated with criteria.

| Criteria | Importance Levels | | | | | Total Scores | Weights |
|---|---|---|---|---|---|---|---|
| | $IL_1$ | … | $IL_k$ | … | $IL_p$ | | |
| | Weights of importance levels | | | | | | |
| | $w_1$ | … | $w_k$ | … | $w_p$ | | |
| | vote of each criterion in each ranking place | | | | | | |
| $C_1$ | $v_{11}$ | … | $v_{1k}$ | … | $v_{1p}$ | $TC_1 = \sum_{k=1}^{p} v_{1k} w_k$ | $W_1$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| $C_j$ | $v_{j1}$ | … | $v_{jk}$ | … | $v_{jp}$ | $TC_j = \sum_{k=1}^{p} v_{jk} w_k$ | $W_j$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| $C_m$ | $v_{m1}$ | … | $v_{mk}$ | … | $v_{mp}$ | $TC_m = \sum_{k=1}^{p} v_{mk} w_k$ | $W_m$ |

$IL_1,...,IL_k,...,IL_p$ so that $\{IL_1,...,IL_k,...,IL_p\}$ expresses the importance of more to less and $p$ indicates the number of importance levels. Then the decision makers will be asked to evaluate the criteria on $p$ importance levels. $v_{jk}$ is the number of decision makers who evaluate the importance level of criterion $j$ on $IL_k$ level. The weights are calculated for each candidate by utilizing the DEA method based on the linear programming and then the total score of the candidate should be maximized according to its objective function. The model proposed in (2), is ran for each candidate once and after calculating the total score, eventually the candidate with the highest total score out of one will be introduced as an efficient option. Thus the viewpoints of a number of experts and mining PhD candidates about the significant of sustainable development criteria affecting open pit mine design, has been collected with a questionnaire.

### *3.5. The weights of sustainable development sub-criteria affecting open pit mine design*

By utilizing the proposed model, the importance of sustainable development of sub-criteria affecting the open pit mine design are obtained as shown in table 3.

Table 3. The importance of sustainable development sub-criteria affecting open pit mine design.

| Abbreviation | criteria | Score of Each Criterion | Normalized Weight |
|---|---|---|---|
| $C_1$ | Water pollution[1] | 2.75 | 0.0256 |
| $C_2$ | Final product price[2] | 2.75 | 0.0256 |
| $C_3$ | Recycle or dispose of mine hazardous waste | 2.417 | 0.0225 |
| $C_4$ | Mineral resources use | 2.417 | 0.0225 |
| | ……………………………… | | |
| $C_{73}$ | Ore type | 0.75 | 0.007 |
| $C_{74}$ | The maximum potential of consumption of final mine product | 0.668 | 0.0062 |
| $C_{75}$ | Costs related to stock pile | 0.667 | 0.0062 |
| $C_{76}$ | Share of GDP (%) | 0.501 | 0.0047 |
| $C_{77}$ | Post mining incomes | 0.5 | 0.0047 |

## 4. Results and discussion

The mining industry has a significant share in the world economy and the development plans by providing raw materials, according to increasing the world population and growing needs of various industries to minerals. In the developing countries, the lack of attention to the sustainable development aspects simultaneously, causes undesirable impacts and preventing the sustainable growth in mining. By analysing the local communities surrounding the mines in developing countries, it can be realized the low livelihood standards, environmental pollutions, social anomalies, crime and unemployment, are similarities of these regions. The reason is a neglect of environmental and social aspects alongside economic benefits.

Nowadays, increasing demand for the minerals, technology development and economic growth, increases deep mining of low grade reserves.

Due to the most important challenges that the mining industry is facing are, the allocating a significant portion of land under pits of mines, waste dumps and tailing dams, mine closure and reclamation method for other mined-lands uses and prioritization of projects with lower environmental, socio-economic risks, consider the mining activities in the framework of sustainability. On the other hand, sustainable mine design includes determining the ultimate pit limit and planning of optimum annual production with the aim of maximizing the net present value as the constraints of mining and sustainable development principles are considered. The nested sustainable development model implies a close correlation between the aspects of sustainability. The economy is defined as a subsystem of society and similarly the society is executable in the broader field as environment.

In the surveys taken, the share of each main sustainable development criterion affecting open pit mine design is shown in Table 4.

Table 4. The weights of sustainable development criteria affecting the open pit mine design.

| Classification of Criteria | Total Weights of Criteria | Total Weights of Criteria (%) |
|---|---|---|
| **Environmental** | 0.26 | 26% |
| **Economic** | 0.38 | 38% |
| **Social** | 0.36 | 36% |

It is worth mentioning, it is necessary to consider the three main criteria (environmentally, economically and socially) simultaneously with the same share of 0.33 to design ideally in sustainable development framework but the author intention of this study is not the presentation of a decisive method for estimating and applying all the costs and revenues associated with the environmental, economic and social criteria rather increasing attention to the mining activities in accordance with sustainable development.

## 5. Conclusion

The issue of sustainable development changed the traditional definition of mining and bring forward the term "modern mining" which is composed of five principles including Prospecting, Exploration, Exploitation, Mine closure, and Reclamation. Since considering the sustainability issues in the mine design stage is an appropriate method to reduce the environmental, social and economic risks life and enhance opportunities while mining and post-mining, hence in this study, after identification of sustainable development criteria affecting ultimate pit limits design and calculating the weights of each sub-criterion, it can be determined the synchronization of different ultimate pit limits designs with the sustainable development principles in mining activities. Finally, the amount of compatibility of mine design and sustainable development issue, can be measured via the sum of satisfied criterion weights. The utilization of sustainability criteria in the mine design have reduced the investment risk in the mining industry as much as possible and the government can concede a part of the tasks in the field of social and environmental issues to the mining companies, in addition to the accurate monitoring of mining activities. The author's intention of this study is not the presentation of a definite/ decisive method estimating the weights of environmental, economic and social criteria associated with the sustainable mining, but rather to increase attention to the mining activities with the principles of sustainability in the ultimate pit limit design stage. Consequently, the unique standards in the sustainable development criteria affecting ultimate pit limits design in the metal mines with various ore types can be presented.

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